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GWM: General Weed Management Model

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ABSTRACT

GWM is a decision support system designed for evaluating soil-applied and post-emergence weed management options in row crops. It has a general structure to allow use with different crops. The system consists of a simulation model, databases, and a database management module. The simulation model has a set structure for linking processes of weed population dynamics during a single season, but allows flexibility in how each

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process is modeled. Databases store model parameters, information about management options, and field-specific simulation inputs. The database management module allows a user to specify entirely the simulation model or modify existing versions without programming. GWM has been parameterized to evaluate weed management as in two existing models (WEEDSIM and WEEDCAM) and for dry bean production. The structure of GWM and associated databases appears to capture essential aspects of weed biology influencing management decisions. GWM can be enhanced as knowledge of weed biology and ecology is refined.

INTRODUCTION

Choosing how to manage weeds in a field is a complex, information-intensive task. Ideally, a decision-maker should know the emergence patterns of weeds, the crop's ability to suppress weed growth, the effect of different weed species on crop yield and quality, and the characteristics of possible management options. For each option, the decision-maker should know degree of control of each weed species, cost, and regulatory and biological (crop rotation, weed size, etc.) restrictions on use. All this information must be considered with the decision-maker's objectives and resource constraints and the observed or anticipated mixture of weeds in a field (Auld *et al.*, 1987).

Microcomputer programs have been developed to help decision-makers with choosing weed management (Mortensen & Coble, 1991; Schweizer *et al.*, 1993). These decision support systems are either efficacy-based or population-based (Mortensen & Coble, 1991). Efficacy-based programs help decision-makers by providing faster and easier access to information on herbicide labels and in weed control recommendations guides (Linker *et al.*, 1990; Kells & Black, 1993; Kidder *et al.*, 1989; Renner & Black, 1991; Thomson & Williamson, 1992; Stigliana & Resina, 1993). Information relevant to the weed population in a field can be quickly assembled because microcomputer software can now extract information easily from large databases. Population-based models do the database management functions of efficacy-based models. In addition, these models incorporate information from studies of weed ecology and management in order to predict yield loss from competition and some aspects of weed population dynamics. Population-based models use information that decision-makers might otherwise not see or consider (Thornton, 1985; France, 1988).

Many population-based programs incorporate information about weed biology and ecology through simple, deterministic simulation of management. Examples of population-based programs with an embedded simulation model include HERB (Wilkerson *et al.*, 1991), WEEDSIM (Swinton & King, 1994a) and WEEDCAM (Lybecker *et al.*, 1991). These programs simulate outcomes of management (net gain from weed control, net margin, profit, weeds escaping control) from an estimate of the weed seed bank or seedling population in a field. Several biological processes are modeled to predict outcomes.

Population-based decision support systems can be valuable for decision-makers and researchers. Two such programs have been tested on research and commercial farms. Results suggest decision-makers using these tools can generally achieve appropriate weed control with less herbicide, but without sacrificing profit (Forcella *et al.*, 1993; Schweizer *et al.*, 1993). Researchers developing and parameterizing population-based systems have identified critical gaps in knowledge of weed population dynamics and also significant regional variation in weed biology and ecology (Schweizer *et al.*, 1993). Simulation experiments using population-based models have been substituted for more expensive or impractical field research (Swinton & King, 1994*b*; Wiles *et al.*, 1992*a*; Wiles *et al.*, 1992*b*).

Although useful, population-based weed management models, like other decision support systems, can be costly to develop, distribute and maintain (McClure, 1992, 1993; Berry, 1993; Lambert, 1993). Coding, testing and validating systems, producing users' manuals, and training users can be expensive and time-consuming. Cost of maintenance and support may exceed development costs (Lambert, 1993). Annual updates may be needed to refine parameters as more data on weed biology and ecology are collected and as recommended practices and government regulations evolve. Researchers have had to modify models for regional differences in weed biology, ecology and management practices in order to expand use of a program beyond the originally targeted area (Schweizer *et al.*, 1993; Swinton *et al.*, 1994).

Many of the decision support tools are similar and, as a result, development effort has been redundant and unnecessarily costly (Mortensen & Coble, 1991). Population-based simulation models must model the same processes of weed population dynamics and weed–crop interactions (Schweizer *et al.*, 1993). This similarity is an opportunity to speed development and sharing of these systems by designing a generalized bio-economic simulation model shell. This shell could then be parameterized for weed management decision support in different crops and under various production practices. This paper describes GWM (General Weed Management Model), a decision support system generalized with database structures for specifying weed management options and a simple, bio-economic simulation model with choices for how biological processes are modeled. The system includes a database management module for easily parameterizing the general structure, entering field and farm-specific information, and doing simulations.

STRUCTURE OF THE MODEL

Overview of the program

GWM is a weed management decision support and record-keeping system. It has three components: a bioeconomic simulation model, a set of databases and related index files, and a database management module. The simulation model is written in Visual BASIC Version 1.0 for MS-DOS (Microsoft Corporation, Redmond, WA) with access to databases through db/LIB (AJS Publishing, Los Angeles, CA), a relational database management system implemented as a linkable library. The database management module is written in Clipper Version 5.01 (Nantucket Corporation, Los Angeles, CA). All databases and indices have dbase III (Borland International, Inc., Scotts Valley, CA) file structure. The database management module is the main module of GWM and the decision-maker's interface to the simulation model. Through this module, users view and modify model parameters and candidate recommendations, enter information specific to a farm and field, and run the simulation model.

The bioeconomic simulation model predicts the effect of management on weed population dynamics and crop yield in a single season. These effects are simulated from an estimate of the weed seed bank or seedling population in a field. To evaluate soil-applied management options, the model simulates full season management (soil-applied followed by post-emergence) from estimates of the seed bank. Post-emergence management options also can be evaluated from estimates of the seedling population.

Besides weed population estimates, the user must supply other field-specific information. This includes predicted weed-free yield and crop selling price, row spacing, planting date, and next year's crop and other field-specific conditions that may affect the choice of weed management options (Fig. 1). Before any simulations are done, the program identifies which management options are feasible (Fig. 2). For an option to be feasible, it must satisfy two conditions. First, it must have efficacy greater than zero for at least one of the weed species present. It must also have no restrictions, such as crop rotation and crop or weed size, which would prohibit use of the option for the specified field conditions. All feasible options and no management are simulated. The user can view a ranked list of the top 49 management options, as well as no management (Fig. 3).

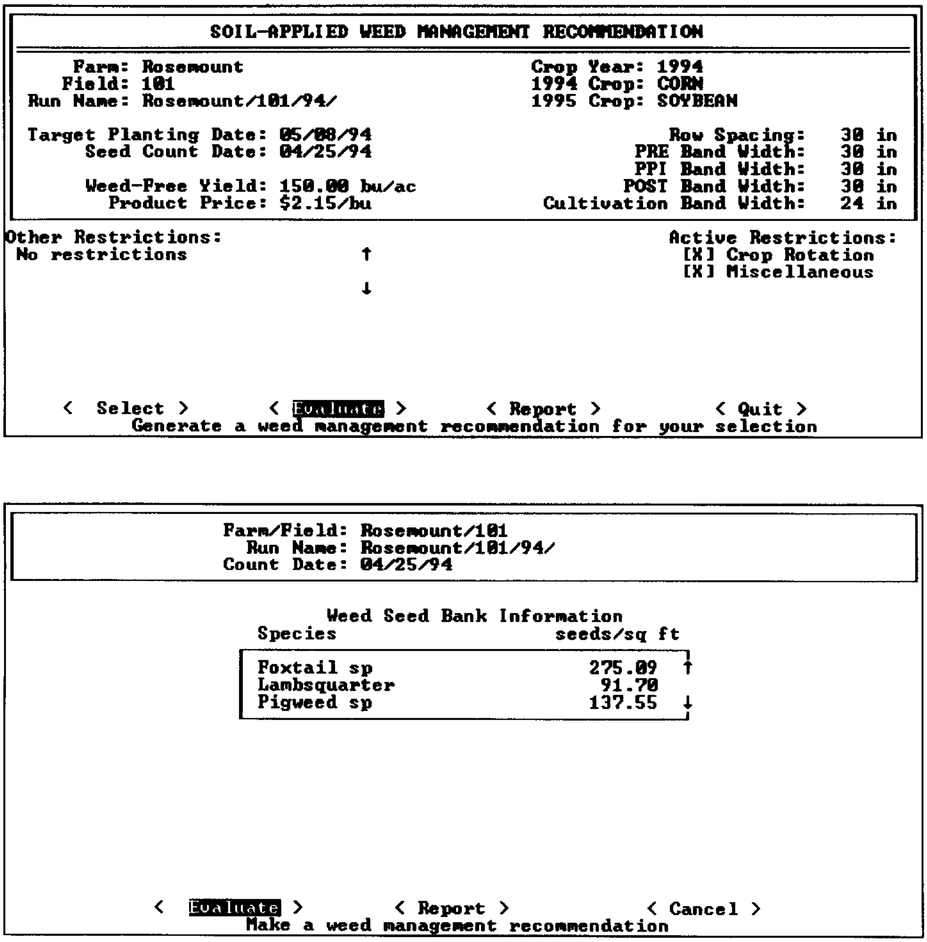


Fig. 1. Screens displaying required field-specific information for a soil-applied evaluation.

Options are ranked according to net gain from weed management. For any option, the user may display details about the cost, timing and components of the option and expected population of escapes and either the seed bank population or weed seed production (Fig. 4). Some of this information can be viewed in graphs.

Biological processes that can be simulated include weed emergence over time, crop yield loss from weed competition, efficacy of weed control, weed seed production and seed bank mortality, and yield penalty for planting a crop late. Most processes can be modeled to vary with composition of the weed population and time of weed and crop emergence. The weed population is divided into cohorts to capture the effect of the time of weed emergence on weed seed production and on competition with the crop.

Specifying weed management options

GWM can simulate chemical and mechanical weed management practices. Practices can vary in cost, efficacy, period of activity and

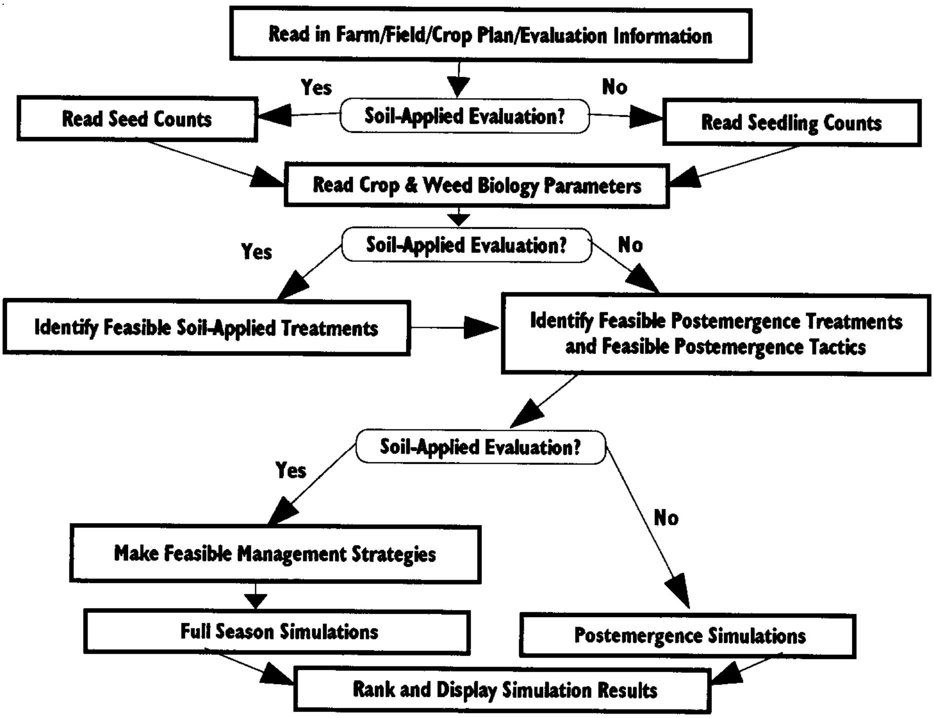
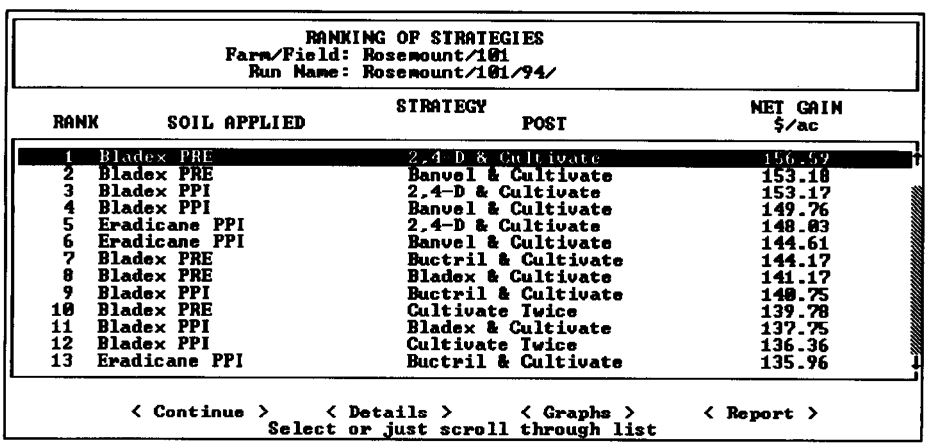


Fig. 2. Flow chart of the recommendations module.


RANKING OF STRATEGIES
Farm/Field: Rosemount/101
Run Name: Rosemount/101/94/

RANK	SOIL APPLIED	STRATEGY POST	NET GAIN $/ac
1	Bladex PRE	2,4-D & Cultivate	156.59
2	Bladex PRE	Banvel & Cultivate	153.18
3	Bladex PPI	2,4-D & Cultivate	153.17
4	Bladex PPI	Banvel & Cultivate	149.76
5	Eradicane PPI	2,4-D & Cultivate	148.03
6	Eradicane PPI	Banvel & Cultivate	144.61
7	Bladex PRE	Buctril & Cultivate	144.17
8	Bladex PRE	Bladex & Cultivate	141.17
9	Bladex PPI	Buctril & Cultivate	140.75
10	Bladex PRE	Cultivate Twice	139.78
11	Bladex PPI	Bladex & Cultivate	137.75
12	Bladex PPI	Cultivate Twice	136.36
13	Eradicane PPI	Buctril & Cultivate	135.96

< Continue > < Details > < Graphs > < Report >
Select or just scroll through list

Fig. 3. Screen displaying ranking of management options for a soil-applied evaluation.

restrictions on use. For practices to be simulated correctly, each must be described with a four-layer hierarchical structure of elements. The database management system guides the user through specifying practices according to this structure.

The four elements of the hierarchy, from bottom to top, are components, treatments, tactics and strategies (Table 1). Each element has its own characteristics. For example, treatments have the characteristics of cost and efficacy. Higher level elements are composed of one or more of the lower level elements and may 'derive' or 'inherit' some characteristics from the lower level elements besides having user-defined characteristics.

Mechanical operations and herbicides are components. Cost is one characteristic of a component. Herbicides also have the characteristic of

```
                    MANAGEMENT STRATEGY RANKED #  1
                 Farm/Field: Rosemount/101
                   Run Name: Rosemount/101/94/

 Bladex PRE/2,4-D  Cultivate                       COST:$     25.28/ac

PRE/PPI  05/08/94 Bladex PRE                                  20.02
                  Bladex 90DF  3 lb ai/ac            18.62
                  PRE Application                     1.40
POST     05/29/94 2,4-D Amine                                  2.76
                  2,4-D Amine  .5 lb ai/ac            1.36
                  POST Application                    1.40
POST     06/12/94 Cultivate                                    2.50
                  Cultivation                         2.50


                   Profit: $   55.22/ac          Yield: 96.1 bu/ac
  Net Gain from Weed Control: $  156.59/ac     Yield Loss: 36 %

                         < Continue >
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                    MANAGEMENT STRATEGY RANKED #  1
                 Farm/Field: Rosemount/101
                   Run Name: Rosemount/101/94/

                                      End of the Season
                                  Weed Population      Seed Population
  Species                           plants/sq ft         seeds/sq ft

Foxtail sp                              1.54               313.21
Lambsquarter                             .45                81.18
Pigweed sp                               .44               196.27



                 < Continue >           < Report >
                   Return to ranked list of results
```

Fig. 4. Screens displaying detailed information about a management option of a soil-applied evaluation.

TABLE 1
Elements for Describing Management Options

Name	Type	Characteristics: User-defined	Characteristics: Inherited
Strategy		—	Name Cost Species efficacies Period of activity for soil-applied efficacy Crop rotation restrictions Miscellaneous restrictions
Tactic	Post-emergence	Name Treatments (up to three) Timing of treatments (days after planting)	Cost Species efficacies Crop rotation restrictions Miscellaneous restrictions Crop size restrictions Weed size restrictions
Treatment	Post-emergence	Name Components (up to three each of herbicides and mechanical operations) Herbicide rates Species efficacies Crop rotation restrictions Miscellaneous restrictions Crop size restrictions Weed size restrictions	Cost
	Soil-applied	Name Components (up to three each of herbicides and mechanical operations) Herbicide rates Species efficacies Period of activity for efficacy Crop rotation restrictions Miscellaneous restrictions	Cost
Component	Herbicide	Name Cost Application unit	—
	Mechanical operation	Name Cost	—

application unit. Examples of mechanical operations include rotary hoe, cultivation and herbicide application or incorporation. The next level is treatments. Treatments are either soil-applied or post-emergence. A treatment is a weed control practice that is assigned species efficacies. It may consist of up to three mechanical operations and up to three herbicides. Herbicide rates are specified at the treatment level and the cost of a treatment is derived from cost of its components. Efficacy, by species, is a characteristic of both types of treatments. A soil-applied treatment also has a period of activity for efficacy. Examples of a treatment are application of a single herbicide, application of a tank mixture of herbicides and cultivation.

Restrictions are a characteristic of treatments. Restrictions are conditions that, when true for a field, should prohibit use of a treatment. For example, a treatment assigned the crop rotation restriction 'sugarbeets' will not be evaluated if sugarbeets are specified as the next season's crop for a field. Types of restrictions are crop rotation, crop and weed size (post-emergence treatments only) and miscellaneous. Weed and crop size restrictions are the maximum and/or minimum height or number of leaves. Users may attach an unlimited number of all types of restrictions to a treatment, but only post-emergence treatments may have crop and weed size restrictions.

A post-emergence tactic is a series of post-emergence treatments applied in a specified time sequence of days after planting. A tactic may consist of up to three treatments. A tactic inherits or derives its cost, efficacy and restrictions from the treatments. A sequential herbicide application is a tactic with two treatments. Cultivation followed by a herbicide application is another tactic with two treatments.

A strategy is a combination of a soil-applied treatment with a post-emergence tactic. While users create tactics from post-emergence treatments, the model creates strategies. Strategies are all combinations of feasible soil-applied treatments and no soil-applied management with all feasible post-emergence tactics and no post-emergence management.

Cohorts of a weed population

Depending on when a weed emerges, it may compete with the crop, interfere in harvest, reduce crop quality and produce seeds. When weed emergence over time is modeled, GWM can distribute weeds between three 'functional' cohorts. These cohorts group weeds that, because of the time of emergence, similarly affect the outcome of weed management.

Weeds that emerge before or on the day of planting are in cohort 1. It is assumed that field preparation kills cohort 1 weeds. Weeds emerging with or after the crop are in the second and third cohorts. The second cohort emerges during the crop's required weed-free period. Weeds of cohort 2 compete with the crop and produce seed. The model includes a third cohort to capture reduced competitiveness and seed production by weeds emerging after the crop's required weed-free period. Weeds of cohort 3 do not compete with the crop but do produce seed. Cohorts 2 and 3 may have different seed production functions. The number of individuals in each cohort can vary with crop planting and harvest dates, the crop's ability to compete with weeds and suppress weed emergence, and the pattern of weed emergence over time. A user can choose to have all weeds emerging with or after the crop belong to cohort 2, the competitive cohort.

Structure of the simulation model

Weed management is evaluated with deterministic, discrete-event simulations. A simulation run models the outcome of a single management strategy or post-emergence tactic for one season. An evaluation is a series of simulation runs under one set of input variables (planting date, weed-free yield, population estimates, etc.). State variables are defined by weed species: emerged weeds ($ewds_i$ for species i), controlled weeds ($cwds_i$), number in each cohort ($co1_i$, $co2_i$, $co3_i$) and seeds in the seed bank (sds_{ji}, $j = 0$ for the initial seed bank and $j = 1$ for the seed bank at the end of season) (Table 2). Population estimates may be for a unit area or length of crop row. Herbicide rate may be expressed as actual product or active ingredient. Results may be displayed in English or metric units with costs and profit as \$ ha^{-1} or \$ acre^{-1}.

TABLE 2
State Variables

Name	*Description*	*Units*[a]
sd_{ji}	Seed bank of species i at beginning of the season (j = 0) or end of the season (j = 1)	seeds m^{-1} seeds m^{-2}
$ewds_i$	Emerged plants of species i	plants m^{-1} plants m^{-2}
$cwds_i$	Number of plants of species i controlled	plants m^{-1} plants m^{-2}
$co1_i$	Plants of species i that emerge before or on the day of planting	plants m^{-1} plants m^{-2}
$co2_i$	Plants of species i that emerge during the crop's required weed-free period	plants m^{-1} plants m^{-2}
$co3_i$	Plants of species i that emerge after the crop's required weed-free period	plants m^{-1} plants m^{-2}

[a] Calculations are done in metric units. Results may be displayed in English units.

TABLE 3
Events and Associated Calculations of Full Season Simulations

Event	*Description*	*Calculations*[a]
p	Planting	Update emergence Calculate cohort 1
ec	End of the crop's required weed-free period	Update emergence Update control from soil-applied treatment Calculate cohort 2
ee	Beginning of period when crop canopy development prevents further weed emergence	Update emergence Update control from soil-applied treatment
sa	End of period of activity of a soil-applied treatment	Update emergence Update control from soil-applied treatment
pst	Post-emergence treatment	Update emergence Update control from soil-applied treatment Calculate control from post-emergence treatment
h	Harvest	Update emergence Update control from soil-applied management Calculate cohort 2 Calculate cohort 3 Calculate yield loss from delayed planting Calculate yield loss from competition Calculate yield Calculate seed bank mortality Calculate viable seed production Update seed bank Calculate profit Calculate net gain from weed management End simulation

[a]Calculations are listed in sequential order. Depending on the chronological order of events, not all calculations associated with an event may be done.

Simulations progress according to the event-scheduling approach with state variables updated only when an event occurs (Law & Kelton, 1982). Events are scheduled by day of the year (d_j for event j) and are management activities or biological milestones (Table 3). Management activities include planting (*p*), harvest (*h*), and post-emergence treatment (*pst*). Biological milestones include end of the crop's required weed-free period (*ec*), day when crop canopy development suppresses further weed emergence (*ee*), and end of the period of activity of a soil-applied treatment (*sa*). Planting and harvest are the only events required for a simulation.

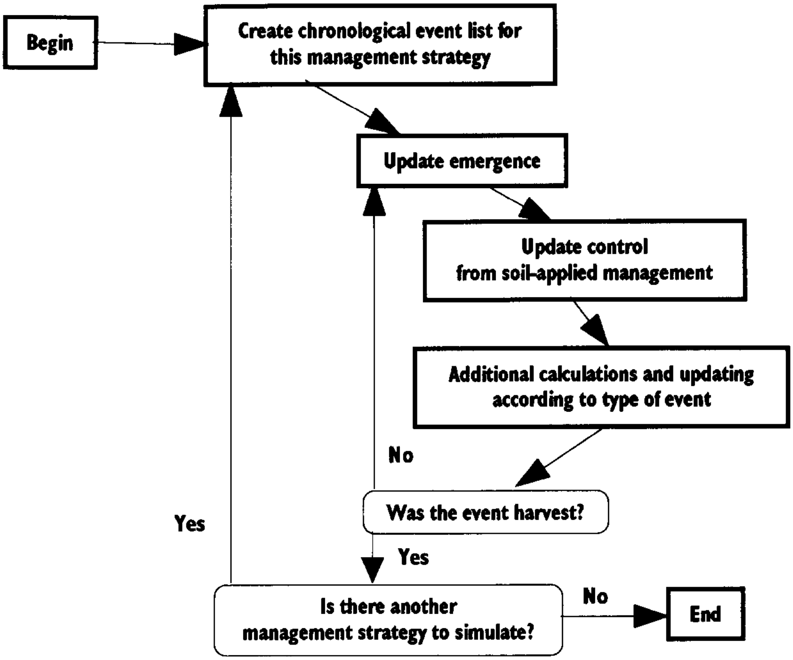

Fig. 5. Flow chart for full season simulations.

Full-season simulations

Simulations for evaluating soil-applied management begin with the event of planting (on day d_p) and end with the event of harvest (on day d_h) (Fig. 5). Processing of any event begins with updating the number of emerged weeds of each species. Emergence is modeled for each species based on an estimate of the seed bank, an estimate of the maximum proportion of the initial seed bank that could emerge during the season (m_i), a distribution function relating cumulative emergence to day of the year ($f_i(d)$), and an estimate of the day when crop canopy development will prevent further emergence (d_{ee}):

$$ewds_i(d_{ev}) = \begin{cases} m_i f_i(d_{ev}) sds_{0i} & \text{if } d_{ev} < d_{ee} \\ m_i f_i(d_{ee}) sds_{0i} & \text{if } d_{ev} \geq d_{ee} \end{cases} \qquad (1)$$

where $ewds_i(d_{ev})$ is the number of weeds of species i that have emerged by the day of event ev. There are several functions to distribute emergence over time or all weeds may be assumed to emerge with the crop. The effect of crop canopy development on emergence may be disabled.

The next step in processing an event is to update the number of controlled weeds for soil-applied efficacy if the event occurs during the period of activity of a soil-applied treatment. Efficacy is per cent control of a species. It is assumed that soil-applied treatments are applied on the day of planting (d_p) and efficacy is constant throughout the period of activity:

$$cwds_i(d_{ev}) = \begin{cases} cwds_i(d_{ev-1}) + (ewds_i(d_{ev}) - ewds_i(d_{ev-1}))saeff_{ti} & \text{if } d_p < d_{ev} \leq d_{sa} \\ cwds_i(d_{ev-1}) & \text{if } d_{ev} > d_{sa} \end{cases} \quad (2)$$

where $cwds_i(d_{ev})$ is cumulative number of weeds controlled, d_{ev-1} is day of the event before event ev and $saeff_{ti}$ is efficacy of soil-applied treatment t for species i, $(0 \leq saeff_{ti} \leq 1)$.

Post-emergence treatments only control weeds that are present on the day of application. When an event is post-emergence treatment ($d_{ev} = d_{pst}$), the number of controlled weeds is updated as:

$$cwds_i(d_{ev}) = cwds_i(d_{ev-1}) + (ewds_i(d_{ev}) - cwds_i(d_{ev-1}))\, psteff_{ti} \quad (3)$$

where $psteff_{ti}$ is efficacy of post-emergence treatment t for species i, $(0 \leq psteff_{ti} \leq 1)$. Other events in a simulation are included so cohorts are calculated correctly:

$$\begin{aligned} \text{co1}_i &= ewds_i(d_p) \\ \text{co2}_i &= \begin{cases} ewds_i(d_{ec}) - cwds_i(d_{ec}) & \text{if } d_{ec} \leq d_h \\ ewds_i(d_h) - cwds_i(d_h) & \text{if } d_{ec} > d_h \end{cases} \\ \text{co3}_i &= ewds_i(d_h) - cwds_i(d_h) - \text{co2}_i. \end{aligned} \quad (4)$$

Harvest ends the simulation and several measures of the value of weed management are calculated. Expected yield is calculated from the decision-maker's estimate of weed-free yield (yld_{wf}) and predictions of proportion of yield lost from competition with weeds (yl_{wc}) and proportion of yield lost from a delay in planting (yl_{pd}):

$$yld = yld_{wf}(1-yl_{dp})(1-yl_{wc}). \quad (5)$$

Expected yield loss from delayed planting is calculated from the planting date (d_p):

$$yl_{dp} = f(d_p). \quad (6)$$

Only cohort 2 weeds compete with the crop in this model. Yield loss from competition with cohort 2 weeds is calculated from a single yield loss function (f_{yl}) and a set of competitive indices (ci_i for species i) for the N species present (Lybecker *et al.*, 1991; Wilkerson *et al.*, 1991):

$$yl_{wc} = f_{yl}(\sum_{i=1}^{N} ci_i \text{co2}_i) \quad (7)$$

Conceptually, this approach may be thought of as converting a mixed weed population to a population of a standard species and then estimating the yield loss from that single-species population. The yield loss equation relates proportion of yield lost to population of the standard species. Competitive indices reflect the relative competitiveness of species and may be estimated by expert opinion (Lybecker *et al.*, 1991; Black & Dyson, 1993) or by analysis of weed/crop competition experiments with single species (Coble, 1986; Coble & Mortensen, 1992) or species mixtures (Hume, 1993; Swinton *et al.*, 1994).

Profit is calculated from simulated yield (yld), cost of weed management (c_c) and the decision-maker's estimate of selling price of the crop (p_s) and costs other than those associated with weed management (c_{oc}):

$$\text{profit} = p_s\, yld - c_c - c_{oc}. \tag{8}$$

Expected net gain from weed management is calculated from predicted yield with no weed management (yld_{nc}) and predicted yield with management (yld_c):

$$\text{gain} = (yld_c - yld_{nc})p_s - c_c. \tag{9}$$

Seed production is calculated and the seed bank is updated to address growers' concern about weeds escaping in the current year creating future weed problems. Seed production and viability is specified by cohort:

$$psds_i = f_{2i}(\text{co}2_i)v_{2i} + f_{3i}(\text{co}_{3i})v_{3i} \tag{10}$$

where $psds_i$ is number of viable seeds produced by species i, f_{ji} is a function for seed production by species i of cohort j and v_{ji} is per cent viability of those seeds. The seed bank is updated for emergence, seed production, and mortality:

$$sds_{1i} = (1 - k_i)sds_{0i} - ewds_i(d_h) + psds_i \tag{11}$$

where sds_{0i} is the initial seed bank of species i, sds_{1i} is the seed bank at the end of the simulated season and k_i is the proportion of the initial seed bank which will die by harvest.

Post-emergence simulations

Simulations for evaluating post-emergence management are based on the user's estimate of the seedling population in a field. In these simulations, emergence is not simulated, all weeds are assumed to be cohort 2, and the only events are application of a post-emergence treatment and harvest. There is no seed bank, but seed production is calculated.

Flexibility of the simulation model

The simulation model defines one method for linking equations or simple, empirical models of biological processes to evaluate weed management. The flexibility is in choosing from a set of predefined functional forms for modeling each process and in specifying parameters for the selected functions.

DISCUSSION

The general model concept

GWM was designed with a general structure so it could be a weed management decision support system for a variety of annual row crops and in different regions. The program includes an easy-to-use database management module. Through this module, a user can create or modify a simple decision support system without editing ASCII files or programming. A user's version may be as simple as a model that assumes all weeds emerge with the crop. Optimal strategy will then depend on per cent emergence by species, expected crop yield and selling price, and treatment costs and efficacies. The most sophisticated version can model weed emergence over time with the population divided into an early emerging, competitive cohort and a later emerging, non-competitive cohort with reduced seed production. Then the optimal strategy may vary with period of activity of soil-applied treatments, timing of post-emergence treatments, planting date, end of the crop's required weed-free period, and time when crop development suppresses weed emergence.

A test of the usefulness of the general structure of GWM is to parameterize GWM for evaluating weed management in two or more crops. Parameterizing GWM involves describing management options using the model's hierarchical approach and choosing functional forms and specifying parameters for the simulation model. We parameterized GWM to evaluate weed management as it is done in WEEDSIM (Swinton & King, 1994*a*), a model for corn and soybean production in the Midwest. We also parameterized GWM to evaluate weed management as it is done in WEEDCAM (Lybecker *et al.*, 1991), a model for irrigated corn production in Colorado. WEEDSIM and WEEDCAM have been validated on research farms or in commercial fields (Lybecker *et al.*, 1991; Buhler *et al.*, 1993; Forcella *et al.*, 1993).

Management strategies evaluated in WEEDSIM and WEEDCAM could be described with the hierarchical structure of GWM. The generalized bioeconomic simulation model of GWM could accommodate most of the structure and functionality of the simulations of WEEDSIM and WEEDCAM. Differences were minor. GWM could be parameterized to calculate yield loss and weed populations dynamics exactly as in WEEDCAM, but WEEDCAM evaluates more restrictions on herbicide use and calculates herbicide rates according to soil type. Modeling of weed emergence was the major difference between the simulations of WEEDSIM and those of GWM parameterized as WEEDSIM. WEEDSIM uses a discrete function to model weed emergence over time while GWM uses continuous functions. With a continuous function for emergence, the composition of the cohorts can vary with planting date, time of treatments and period of activity of soil-applied treatments. However, modeling emergence with a continuous function requires more detailed information on weed emergence and the efficacy of soil-applied treatments.

Versions of GWM have been parameterized for irrigated dry bean production in Colorado, Wyoming and Nebraska. These versions are being validated on research farms. All of these simulate three cohorts of weeds and model weed emergence over time to address concern about late emerging weeds in dry bean. Late-emerging weeds do not compete with the crop, but may interfere with harvesting or reduce crop quality (Majek, 1984; Westra & Van Gessel, 1993). Again, the generalized structure of GWM was adequate to capture critical features of weed management decisions in dry bean except the effect of weeds on harvesting efficiency and crop quality. Crop quality and harvesting efficiency equations or submodels were not included in GWM because of the lack of information to model these effects. GWM might also be more valuable for dry bean weed management if it included a phytotoxicity submodel since some herbicides treatments may injure dry bean (Wilson & Miller, 1991; Park & Hamill, 1993).

The simulation model of GWM is very simple. Our experience parameterizing GWM suggests that the simple structure is not the greatest obstacle to using GWM. A greater obstacle is lack of information about weed biology, ecology and control. Expert opinion and simplifying assumptions were used often. For example, expert opinion was used for estimating the period of activity of soil-applied treatments and no decay of efficacy throughout this period was assumed. Parameterizing processes of weed population dynamics was more difficult and relied more on expert opinion than specifying treatments and treatment effects. There is little information for predicting weed seed production and seed bank mortality. This information will be critical for predicting the effect of weed management in the current season on later seasons (Schweizer *et al.*, 1993).

Flexibility of GWM

GWM was designed to be expanded as our understanding of weed ecology and population dynamics becomes more sophisticated. The model is not limited to weed density as the measure of weed population. Weed leaf area or relative weed and crop leaf area may be more accurate predictors of crop yield loss than density (Ghersa & Martinez-Ghersa, 1991; Kropff & Lotz, 1992; Morin *et al.*, 1993). Weed biomass or leaf area may be the measure of weed population if all processes are based on this measure, or appropriate conversions are done where needed. For example, in a sugar-beet weed management model, the weed population dynamics are based on density, but yield loss is predicted from weed biomass. A hyperbolic function is used to convert density to weed biomass (Schribbs *et al.*, 1990).

GWM is not limited to scheduling events according to day of the year. Because biological processes are influenced by environmental conditions, decision-making may be improved when some processes are modeled on an environmental calendar. For example, weed emergence may be more accurately predicted from weather data (Alm *et al.*, 1993; Forcella, 1993; Harvey & Forcella, 1993) or efficacy of some post-emergence herbicides may be predicted from environmental conditions at or just before application (Jensen & Kudsk, 1988). In other cases, real-time weather data may not be useful, but historical weather data can be used to examine the inherent, weather-related uncertainty and risk of weed management decisions. Because GWM is an event-driven model, events may be scheduled on an environmental calendar, such as degree days, and use of day of the year and environmental scheduling may be mixed.

Decision-makers often plan weed management within the context of a crop rotation and rotation can be an effective management tool (Zimdahl, 1993). One motivation for developing GWM was to have a set of similar weed-management decision support systems for different crops. Then these systems could be easily linked to evaluate weed management during a crop rotation. An estimate of the weed seed bank is needed for a full season simulation in GWM and this estimate is updated according to weed management during the season. However, multiple-year simulations have not yet been implemented. The challenge for multiple-year simulations will be developing an algorithm for identifying which management options should be tested as initial conditions for simulating the rest of the rotation. In a single season simulation, all feasible options are simulated to find the top 49 options. Simulating all feasible options would be too time-consuming for multiple-year simulations. Swinton & King (1994*a*) developed a model for multiple-year simulations, but for only a two-year rotation and a limited number of weed control options.

GWM may be a convenient format for sharing models of weed biology and ecology. An easy way for users to modify model parameters and inputs is an important feature for weed-management decision support models since recommendations and herbicide labels are often updated annually and weed biology and production practices vary between regions (Teng & Savary, 1992; Foster, 1993; Schweizer *et al.*, 1993; Stigliani & Resina, 1993). Existing weed-management decision support systems offer this access (Linker *et al.*, 1990). GWM users may easily view and modify parameters and inputs through the database management module. Simulation models with modular design and libraries of submodels can facilitate widespread use of models (Hodges *et al.*, 1992; Teng & Savary, 1992). Currently, GWM users are limited to choosing among a set of functions for modeling each process. However, the design of GWM should make it possible to incorporate submodels as choices for modelling processes.

Features of GWM for decision-makers

Decision support systems should relieve decision-makers of the time-consuming task of compiling relevant information. Recommendations from these systems are most useful when data from multiple sources are integrated (Goodell *et al.*, 1993). GWM compiles and uses relevant information from herbicide labels, weed control guides, research experiments and the experience of experts.

Decision support systems should not make a decision, but instead should provide the decision-makers with information on a variety of choices (Coulson & Saunders, 1987). GWM provides information on the expected net financial gain from weed management, seed production and seed bank dynamics for up to 49 options. This feature is important because a decision-maker may have other objectives than maximizing profit (Auld *et al.*, 1987). Also, net gain and profit with several options may be so similar that a decision-maker may wish to choose according to another criterion.

GWM was not designed to model weed biology and ecology in detail, but to model biology well enough to improve decision-making over current practice. The simplicity of GWM maximizes the speed of evaluations, reduces the burden of supplying field and farm-specific information, and helps ensure the model is appropriate for several crops. Decision-makers may need to learn just one program for weed management in all their crops or in important crop rotations.

So far, GWM has only been used for research. However, workshops on using GWM were held in 1995 for a small group of applicators, agricultural consultants, extension personnel and growers. Features of GWM that users liked best included the display of information on seed production, the model's use of restrictions on treatments to exclude options from evaluations based on information on herbicide labels, and the capability to examine the efficacy of different treatments. Users suggested incorporating a less quantitative method than actual counts to describe the composition of the weed population.

Availability of GWM

Copies of this software may be obtained by contacting the second author, R. P. King.

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APPENDIX

TABLE A1
Model Variables and Parameters

Name	*Description*	*Units*
Variables		
d_{ev}	Day of the year for event *ev* ($1 \leq d_{ev} \leq 365$)	
c_c	Cost of weed management	\$ ha^{-1}
c_{oc}	Cost of production other than weed management costs	\$ ha^{-1}
p_s	Selling price of the crop	\$ kg^{-1}
profit	Profit	\$ ha^{-1}
gain	Net gain from weed management	\$ ha^{-1}
$psds_i$	Seed production of species *i*	seeds m^{-1} seeds m^{-2}
yld_c	Yield with weed management	kg ha^{-1}
yld_{nc}	Yield without weed management	kg ha^{-1}
yld_{wf}	Expected weed-free yield	kg ha^{-1}
yl_{dp}	Proportion of yield lost from delayed planting ($0 \leq yl_{dp} \leq 1$)	
yl_{wc}	Proportion of yield lost from competition with weeds ($0 \leq yl_{wc} \leq 1$)	
Parameters		
m_i	Maximum proportion of initial seed bank of species *i* that could emerge during the season ($0 \leq m_i \leq 1$)	
$saeff_{ti}$	Efficacy of soil-applied treatment *t* for species *i* ($0 \leq saeff_{ti} \leq 1$)	
$psteff_{ti}$	Efficacy of post-emergence treatment *t* for species *i* ($0 \leq psteff_{ti} \leq 1$)	
ci_i	Competitive index of species *i* ($0 \leq ci_i \leq 1$)	
v_{ji}	Viability of seed produced by cohort *j* of species *i* ($0 \leq v_{ji} \leq 1$)	
k_i	Proportion of initial seed bank of species *i* that will die by the end of the season ($0 \leq k_i \leq 1$)	